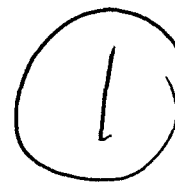


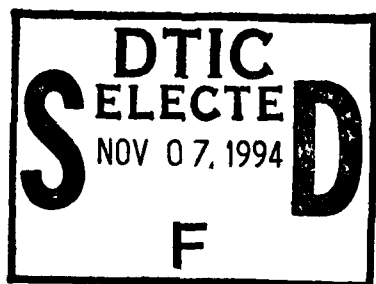
NUWC-NPT Technical Report 10,098  
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# Implementation of a Physics-Scaling Propulsor Noise Model

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Naval Undersea Warfare Center Division  
Newport, Rhode Island

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## **PREFACE**

This report was prepared under the Closed-Cycle ADCAP Propulsion System Special Initiative Assessment Project, program manager J.C.S. Meng (Code 8091C). The sponsoring activity is the Program Executive Office for Undersea Warfare.

The technical reviewer for this report was J.S. Uhlman Jr. (Code 8233).

**Reviewed and Approved: 1 August 1994**

A handwritten signature in black ink, appearing to read 'F. L. White', with a stylized flourish at the end.

**F. L. White**

**Head, Weapons Technology and  
Undersea Systems Department**

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# **IMPLEMENTATION OF A PHYSICS-SCALING PROPULSOR NOISE MODEL**

## **1. INTRODUCTION**

Interest in propulsor noise continues to dominate the field of propulsor experimentation at the Naval Undersea Warfare Center (NUWC) Division, Newport, RI. For over 20 years, NUWC Division Newport and its predecessor activities have performed experiments in an attempt to isolate the contribution of the propulsor to the radiated noise signature of underwater vehicles. Aside from the high cost of such efforts, simulating the flow and operating conditions of the propulsor while maintaining acceptable signal-to-noise ratios is an exceedingly difficult task, making true isolation of the propulsor nearly impossible. Additionally, typical experiments on propulsors as complicated as those incorporated in NUWC Division Newport designs cannot isolate the details of the underlying noise-generating mechanisms, complicating redesign efforts.

In recent years, the Division has participated in the development of a variety of numerical modeling tools. Until recently, however, the focus of these efforts did not include flow-induced noise associated with lifting surfaces, concentration being devoted to the hydromotive aspects of propulsors, and various lines of development in the fields of turbulence modeling and structural acoustics.

This document describes some very recent Division efforts to bring more sophisticated hydroacoustic computational tools on line to supplement the experimental efforts of the Closed-Cycle ADCAP Propulsion System (CCAPS) Special Initiatives Assessment (SIA).

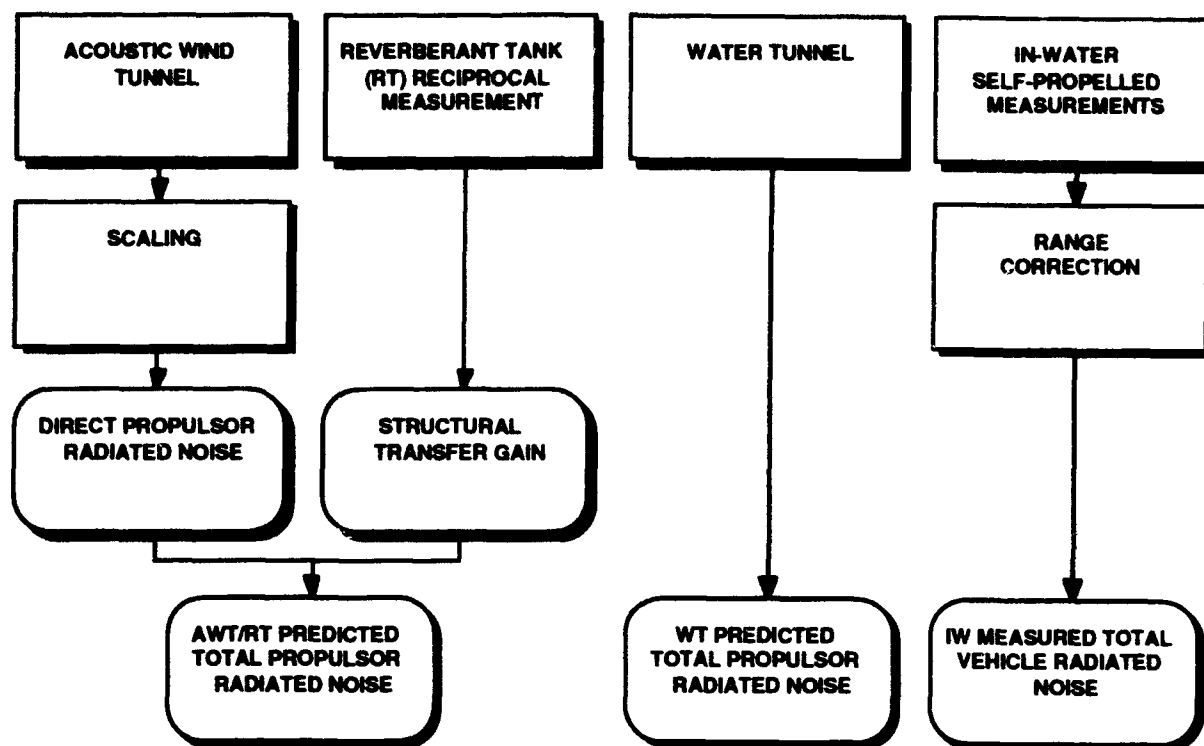
The charter of the CCAPS SIA team was twofold:

1. To perform detailed assessments of various candidate propulsion systems currently under development at the Division for the next generation fleet torpedo, and
2. To provide guidance for future torpedo development based on first-principles rationale and modern military-worth and economic analyses.

One outcome of the CCAPS SIA effort was the implementation of a semianalytic numerical noise model based on physics scaling principles. The most recent version of the computational tool is known as program BBN2. This document describes the implementation of program BBN2 from the initiation of the CCAPS SIA effort through the most recent analyses.

### **1.1 PRE-SIA STATE OF THE ART AT NUWC DIVISION NEWPORT**

Figure 1 depicts the primary procedure for predicting propulsor-radiated noise at the Division prior to the implementation of program BBN2. Essentially, the procedure consists of combining direct radiated noise measurements from an acoustical wind tunnel (AWT) with the transfer gain quantifying structural reradiation from the propulsor and tailcone measured in a reverberant tank (RT) to provide an estimate of the total radiated noise associated with the propulsor.



*Figure 1. Experimental Procedures for Predicting Torpedo Radiated Noise Characteristics*

Because the acoustic impedance between air and most propulsor materials is so mismatched, the flow of air past the propulsor in the AWT does not excite much response in the structure; over the frequency domain of interest, direct noise is by far the dominant component of the measured signal.

Note that the RT measurements are performed reciprocally — i. e., the tank is insonified with white noise and the acceleration excited in the structure is measured using accelerometers fixed at strategic locations on the various components of the propulsor and tailcone. This procedure has some fundamental advantages over direct at-sea measurements:

1. The technique is not contaminated by other torpedo noise sources such as the prime mover and gear train;
2. The intermediate results show the relative importance of direct radiated noise and structurally reradiated noise for a given design;
3. The controlled environments represented by the AWT and RT are not subject to range anomalies and spurious, uncontrollable sources of background noise;
4. The experiments are far less costly than at-sea measurements.

Conversely, there are several disadvantages:

1. Scaling of results from air to water must be carefully performed using somewhat complicated formulae involving frequency, speed, and the acoustical compactness of the propulsor;
2. The reciprocal RT measurements cannot account for modifications to the structurally reradiated noise specifically associated with the flow, namely, convective damping effects;
3. The specific sources of propulsor noise, such as those associated with turbulence ingestion (TI) and trailing-edge (TE) noise, cannot be distinguished from one another;
4. Small design changes, albeit of importance to the acoustical properties of the propulsor, cannot be varied systematically without reassembling costly models with every change.

A competing experimental approach consists of direct measurements of propulsor-radiated noise in a large water tunnel (WT). While subject to disadvantages (3 and 4 above), this approach also has several inherent shortcomings of its own:

1. The frequency range over which the measurements are valid is severely limited by the geometry of the test section;
2. Only the stern aspect of the torpedo can be characterized; and
3. To limit background noise associated with the tunnel structure and the reradiated noise from the excitation of the hull structure by the turbulent boundary layer in the WT is more difficult than in the AWT because the acoustic impedance is not as mismatched in water as it is in air.

## **1.2 SIA NOISE MODELING OBJECTIVES AND ACCOMPLISHMENTS**

Knowing the shortcomings of the various experimental procedures, the SIA team developed the following objectives for assessing propulsor-radiated noise to fulfill its charter:

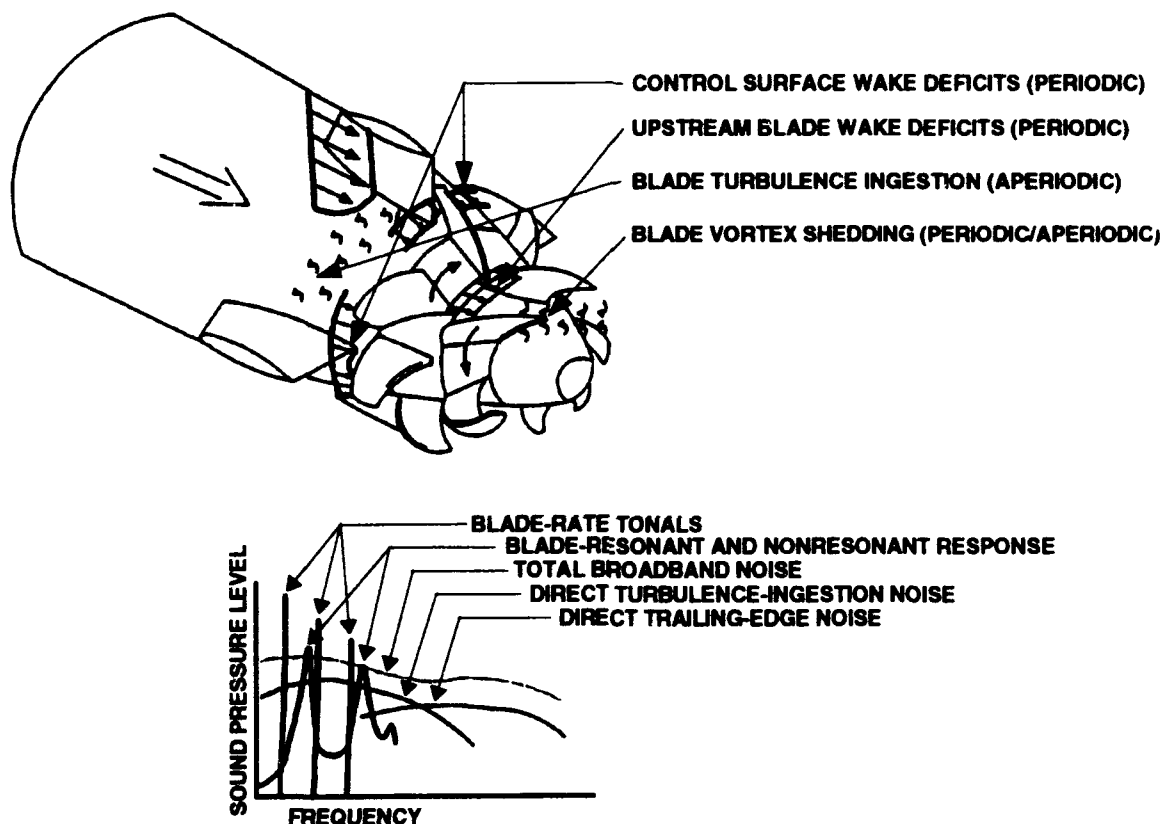
1. Reduce the granularity of the analyses associated with the experimental procedures by developing a model that accounts for the detailed flow past the propulsors, and
2. Use the new model to help assess the various CCAPS SIA candidate propulsors.

Early in the SIA effort, it was discovered that Bolt, Beranek, and Newman (BBN) Systems and Technologies Corporation had implemented an early version of a direct broadband radiated noise model applicable to various propulsor components, including blades and ducts, and to fixed lifting surfaces, such as fins. This early version of the code, entitled program BBN, was acquired, installed, and tested by NUWC Division Newport. With minor modifications to the program, the above objectives could be accomplished. This effort resulted in a new version of the code entitled program BBN2. This new version allowed for more accurate definition of the propulsor geometry, modeling of propulsors having multiple blade rows, and a somewhat more streamlined input scheme. The remainder of the semianalytic propulsor noise modeling effort consisted of code validation and modeling of the various CCAPS SIA candidate propulsors.



### 1.3 OVERVIEW OF THE COMPUTATIONAL TOOL

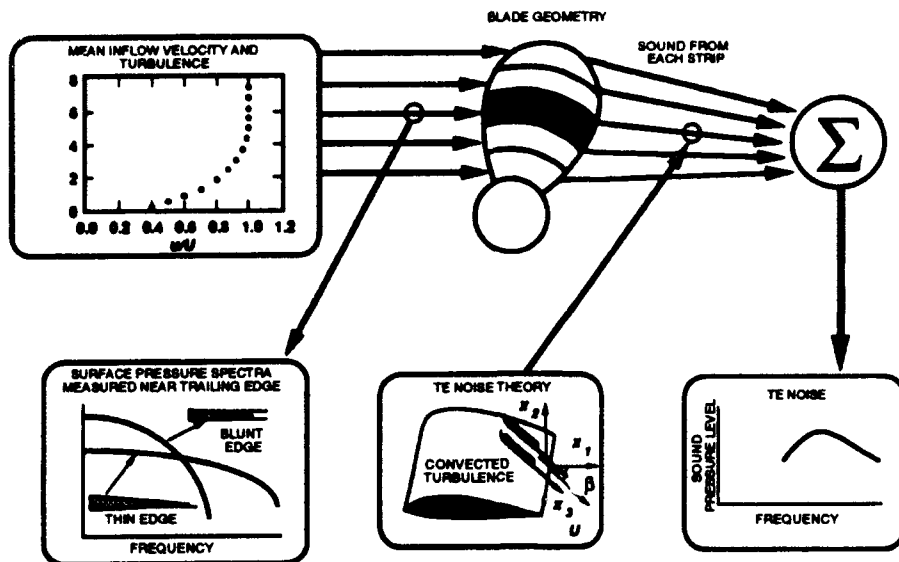
It can be shown that the primary sources of broadband, direct-radiated noise from a lifting surface are due to TI past the leading edge and continuous-spectrum vortex shedding from the trailing edge. Section 2 explains that the direct and reradiated noise problems can be decoupled under a broad range of flow conditions and lifting-surface geometries and structures. Thus, as is depicted in figure 2, the sources of broadband propulsor noise are direct TI noise, direct TE noise, and reradiated noise from hydrodynamic excitation of the structure. Also indicated in figure 2 are nonuniformities in the wake due to nonaxisymmetric features of the vehicle.



*Figure 2. Sources of Broadband Propulsor Direct Radiated Noise*

The model implemented by Breit and Dickinson (1990) applies strip theory to represent the variation in lifting-surface geometry and flow conditions over the span. Then, as is indicated in figure 3, an incoherent acoustic summation is performed over the TI and TE noise sources for all strips, all blades (and bands or ducts, where applicable), and finally over each blade row. The justification and theory underlying this approach are outlined in section 2.

### TE NOISE MODEL



### TI NOISE MODEL

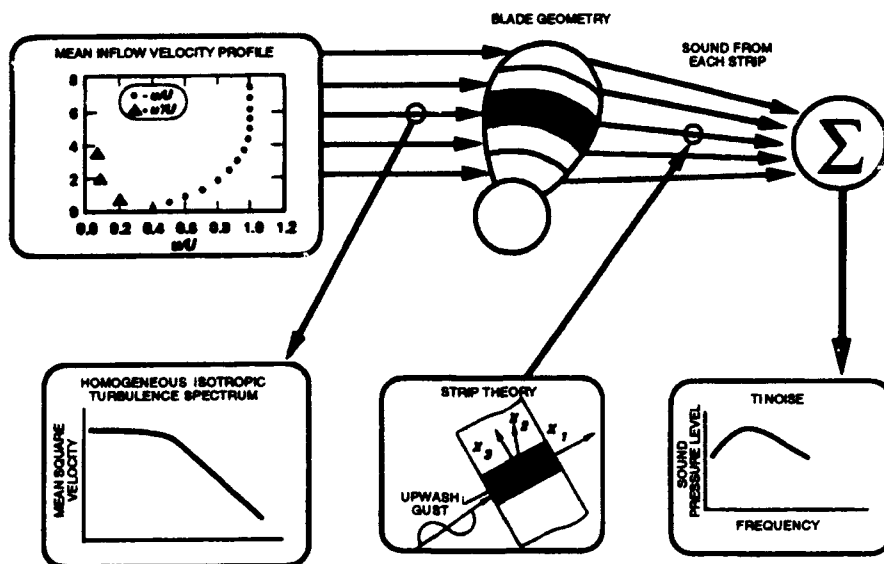


Figure 3. Modeling a Lifting Surface as a Set of Incoherent Noise Sources,  
After Breit and Dickinson (1990)

## 2. THEORETICAL BACKGROUND

The fluctuating pressure, the physical quantity, can be detected by the ear or a mechanical sensor as noise. For the small disturbance flows of interest, from fundamental acoustic theory, the fluctuating density  $\rho'(x, t)$  is related to the fluctuating pressure  $p'(x, t)$  by the expression of equation (1):

$$\rho' = \frac{p'}{c_0^2}, \quad (1)$$

where  $c_0$  is the sound speed in the fluid at the nominal ambient conditions. In understanding the following development, it is important to recall that the target data, the one-third-octave-band (i.e., broadband) source level (i.e., mean square pressure at a specified distance  $r_0$  from the monopole noise source equivalent of the lifting surface), are expressed in decibels (dB) as a function of frequency denoted as  $LS_{1/3}$  in equation (2):

$$LS_{1/3}(f) = 10 \log \left( \frac{\rho_0 c_0}{4\pi r_0^2} \frac{\Pi(f)}{p_0^2} \right) + 10 \log \left( \left( 2^{\frac{1}{6}} - 2^{-\frac{1}{6}} \right) f \right), \quad (2)$$

where:

- $\Pi(f)$  = acoustic power radiated by equivalent monopole noise source
- $\rho_0$  = mean fluid density
- $c_0$  = mean fluid sound speed
- $r_0$  = reference distance from source point (typically 1 m)
- $p_0$  = reference pressure (typically 1  $\mu$ Pa)
- $f$  = acoustic frequency.

The second term in equation (2) converts the narrowband spectral level given by the first term to a one-third-octave-band spectral level. It should be noted that the American National Standards Institute (ANSI, 1976) uses a different specified bandwidth and specific center frequencies.

Goldstein (1976) presents a derivation of the Ffowcs-Williams-Hawkings equation for rigid surfaces shown in equation (3):

$$4\pi c_0^2 \rho' = \sum_{n=1}^4 \mathcal{F}_n, \quad (3)$$

where each term in equation (3) represents an integral over the fluid domain  $S(t_0)$ , the fluid boundary  $v(t_0)$ , or the complement of the fluid domain  $v(t_0)$  as shown in equation (4):

$$\begin{aligned}
\mathcal{F}_1 &= \frac{\partial^2}{\partial x_i \partial x_j} \int_{V(t_0)} \left[ \frac{T_{ij}}{\mathcal{R}} \right]_r dV(\xi) \\
\mathcal{F}_2 &= -\frac{\partial}{\partial x_i} \int_{S(t_0)} \left[ \frac{F_i}{\mathcal{R}} \right]_r dS(\xi) \\
\mathcal{F}_3 &= -\frac{\partial}{\partial x_j} \int_{V(t_0)} \left[ \frac{\rho_0 A_j}{\mathcal{R}} \right]_r dV(\xi) \\
\mathcal{F}_4 &= \frac{\partial^2}{\partial x_i \partial x_j} \int_{V(t_0)} \left[ \frac{\rho_0 V_i V_j}{\mathcal{R}} \right]_r dV(\xi) .
\end{aligned} \tag{4}$$

The notation  $[o]_r$  indicates that the quantity enclosed within the square brackets is to be evaluated in a coordinate system  $\xi$ , which remains fixed with respect to the moving boundaries of the fluid and at the retarded time  $t'$ . This retarded time is determined by solving equation (5):

$$g(t', t, \mathbf{x}, \xi) = t' - t + \frac{r}{c_0} = 0 . \tag{5}$$

Defining the acoustic source point as  $\mathbf{x}'(\xi, t')$ , the various quantities appearing in equations (3) through (5) are

$\mathbf{r}$  = vector from source - to - field point

$$= \mathbf{x} - \mathbf{x}'(\xi, t')$$

$$r = |\mathbf{r}|$$

$M$  = local geometric Mach number

$$= \frac{V}{c_0}$$

$V$  = velocity of a fixed point in  $\xi$

$$= \left. \frac{\partial \mathbf{x}'(\xi, t)}{\partial t} \right|_{\xi = \text{constant}}$$

$A$  = acceleration of a fixed point in  $\xi$

$$= \left. \frac{\partial V(\xi, t)}{\partial t} \right|_{\xi = \text{constant}}$$

$\epsilon$  = viscous stress tensor

$$= \nu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \frac{\partial u_k}{\partial x_k} \right)$$

$T$  = Lighthill's turbulence stress tensor

$$= \rho u_i u_j + \delta_{ij} [p' - c_0^2 \rho'] - \epsilon_{ij}$$

$$F = -n_i (p - p_0) + n_j \epsilon_{ij}$$

= force per unit area exerted by the boundaries on the fluid.

The denominator in each of the integrands is defined below:

$$\mathcal{R}(\xi, t) = r \left| 1 - \frac{\mathbf{r}}{r} \cdot \mathbf{M} \right|.$$

The first term in equation (3) is the quadrupole noise source associated with turbulence in the fluid volume. The second term represents the sound generated by unsteady forces exerted on the fluid by the solid boundaries. The last two terms represent the sound generated as a result of the volume displacement (thickness) effects of the surface. In the derivation of these terms, it is assumed that the volume of the structure enclosed by the surface is constant, so that, in fact, no monopole source generating radiated noise exists in this model. Thus, the third term represents a dipole noise source associated with the acceleration of the surface, while the last term represents a quadrupole source associated with the surface velocity.

A more general form of equation (3), one that does not require that the surfaces be rigid, could provide the theoretical basis for a complete first-principles approach to the propulsor-radiated noise problem. State-of-the-art noise modeling, however, is not nearly developed well enough to support this approach. Thus, the first simplification of the problem (already incorporated within equation (3)) is the decoupling of the structural and hydrodynamic subproblems by retaining the rigid-body assumption.

This simplification is also reflected in the experimental approach, wherein the direct noise and reradiated noise are measured separately, as is described in section 1. In the sense of linear systems theory, the reradiated noise is characterized by a structural transfer function typically obtained from RT measurements, while the direct noise is closely related to the hydrodynamic excitation of the structure. Thus, reduction of the direct noise has the additional benefit of reducing the structurally reradiated noise.

A parallel simplification of the subsonic propulsor-radiated noise problem is the reduction of equation (3) to its farfield form. The applicable equation contains terms associated with quadrupole and dipole sources. Provided the propulsor can be modeled as a set of compact acoustic sources (i. e., as sources for which variations in the retarded time are insignificant), the quadrupole term can be neglected. Goldstein (1976) provides conditions for such an assumption, along with the resulting simplified form of equation (3) as shown in equation (6):

$$4\pi C_0^2 \rho' = -\frac{1}{c_0 \hat{r}^2} \hat{r} \cdot \frac{\partial}{\partial \hat{t}'} \left( \frac{\hat{F}(\hat{t}') - \hat{v}(t_0) \rho_0 \hat{A}(\hat{t}')}{(\hat{C}')} \right), \quad (6)$$

where

$C = \text{Doppler Factor}$

$$= 1 - \frac{\mathbf{r} \cdot \mathbf{M}}{r}$$

$$\hat{F}(t) = -\int_S F(\xi, t) dS(\xi)$$

= total force acting on surface,

and where, except in the case of  $\hat{F}$ , a circumflex over a symbol indicates that the associated quantity is to be evaluated at the center of the source region.

Incorporating the linear-systems decomposition of the structural response, the surface can be assumed to be stationary, and equation (6) reduces to that shown in equation (7):

$$4\pi c_0^2 \rho' = -\frac{\mathbf{x}}{c_0 x^2} \cdot \frac{\partial}{\partial t} \hat{F}\left(t - \frac{x}{c_0}\right), \quad (7)$$

with the force on the surface now given by

$$\hat{F}(t) = -\int_S F(\mathbf{x}', t) dS(\mathbf{x}') .$$

The remainder of the theory presented in this section comprises a method for approximating the dominant components of this force.

Figures 4 and 5 provide flowcharts for the comparison of a prospective first-principles noise model based on the generalized form of equation (3) with the empirical and semiempirical noise models currently in use. The empirical approach schematized in figure 4 includes the so-called Darby noise model using data from AWT and RT measurements. The semiempirical approach depicted in the same figure is represented by program BBN2.

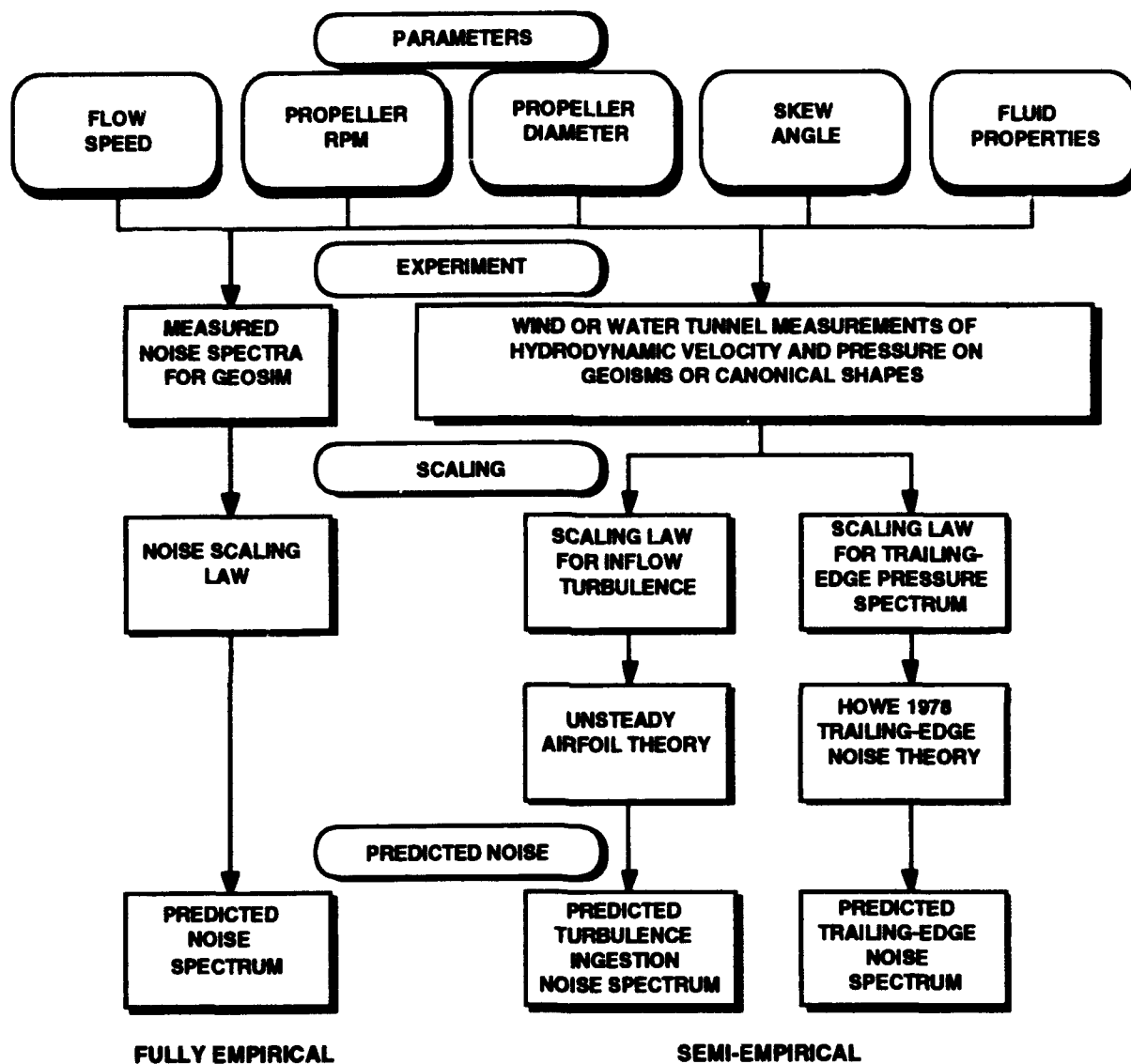


Figure 4. Empirical and Semiempirical Noise Modeling, After Uhlman and Kirschner (1991)

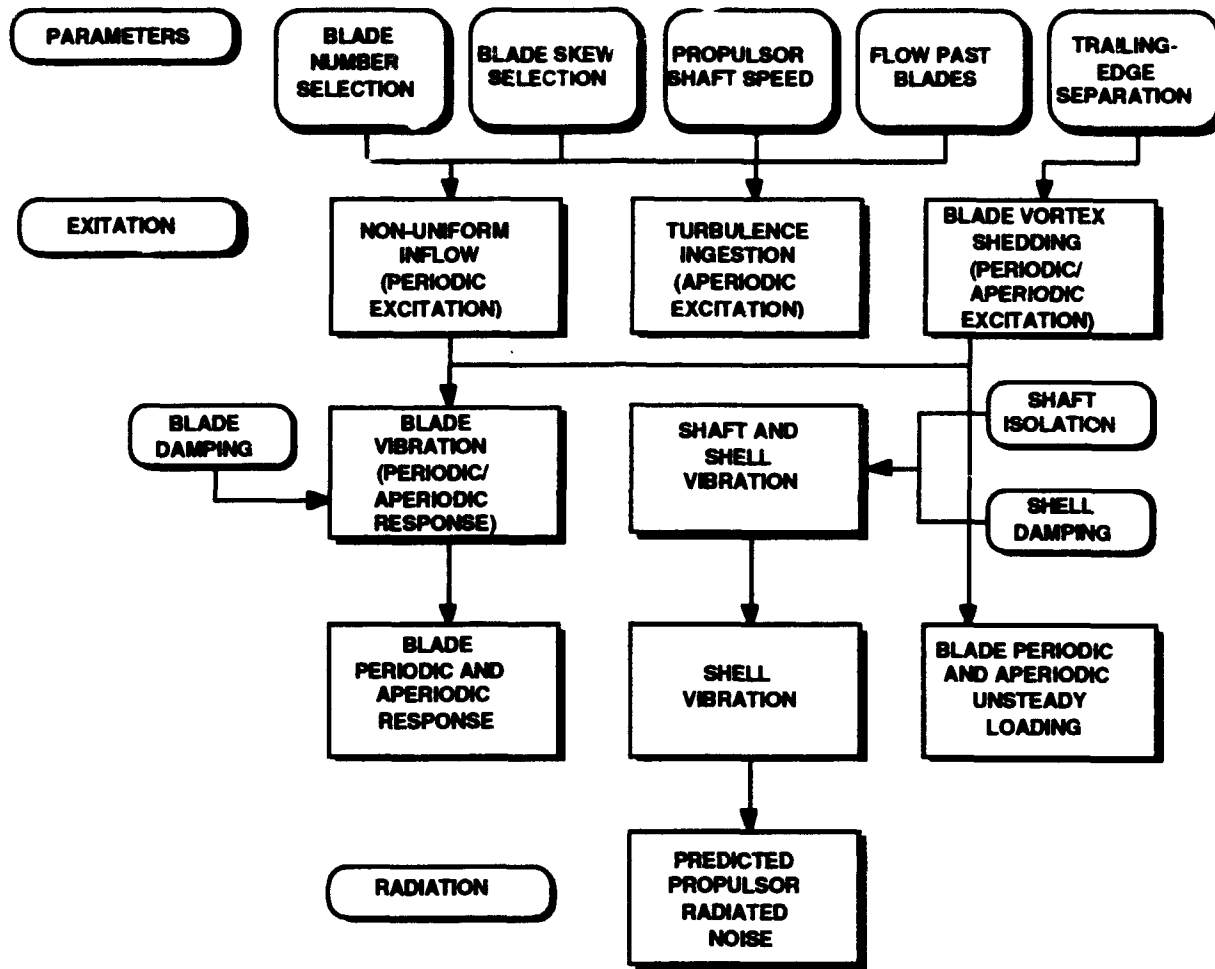


Figure 5. Noise Modeling Based on a First-Principles Approach, After Uhlman and Kirschner (1991)

Figure 5 presents an approach based on first principles. Such a model would involve a series of computationally intensive steps, including the prediction of nonuniform, time-averaged inflow, the turbulence of the inflow, and vortex shedding from lifting surfaces located upstream of the blade row under consideration. The structural computations associated with the first-principles approach would include the prediction of blade response and consequent excitation of the shaft and shell. Finally, the general form of equation (3) would be used to predict the propulsor-radiated noise. Obviously, the development of such an approach would require a substantial investment and remains a distant objective at this time.

The theory implemented in program BBN2 is outlined in Breit and Dickinson (1990) and is reviewed briefly below. The development, presented in two parts, corresponds to the two dominant noise sources: TI noise and TE noise. The models for each of these noise sources are based on strip theory. Under the assumptions outlined below, the total radiated power from the monopole noise source equivalent of each lifting surface  $\Pi(f)$  can be expressed as an incoherent power summation over a set of strips, as shown in equation (8), which divides the lifting surface spanwise, as was shown in figure 3:

$$\Pi(f) = \sum_i \Pi_i(f). \quad (8)$$



The following assumptions apply to both the TI and TE noise models:

1. Changes in blade-section geometry along the span are small compared with the correlation length of the inflow turbulence for the TI model (or the blade turbulent boundary layer at the trailing edge for the TE model);
2. The width of each strip is much greater than the spanwise correlation length of the inflow turbulence (or the blade turbulent boundary layer at the trailing edge) so that the sound radiated by any pair of strips is uncorrelated;
3. Diffraction of the sound from one strip by another is neglected, since the acoustic wavelengths associated with the frequencies are large compared with the strip width and blade chord;
4. The radiated sound is nearly omnidirectional in the farfield, so that each lifting surface of the propulsor is modeled by an equivalent monopole source;
5. Dipole spreading is applicable in the farfield.

## 2.1 OVERVIEW OF TI NOISE MODELING

In modeling the TI noise, the turbulent inflow to each strip is characterized by a turbulence-intensity spectral shape, along with empirically derived turbulence intensity levels and turbulence integral length scales, which are separately specified for each strip. A lift-response function provides the relationship between the TI spectrum represented by a unit sinusoidal upwash gust and the associated farfield direct radiated noise. This quantity should not be confused with the structural transfer function of the lifting surface typically derived from RT measurements.

This strip-theory model is expected to be accurate for turbulent length scales that are small compared with the blade span but large compared with the blade thickness. This assumption is valid for most cases of interest, since the peak of the turbulence-ingestion noise spectrum is associated with the integral length scale of the hull boundary layer turbulence, which is typically small compared with the propeller. In fact, the results of the model tend to be most accurate at the frequency of the peak of the TI noise spectrum.

Under the assumptions listed above, the acoustic power radiated by each strip can be expressed as an integral of the farfield, sound-pressure spectral density over a unit sphere. Breit and Dickinson (1990) apply a result from Amiet (1975) that expresses the spectral density of the farfield sound pressure directly above each strip in terms of the unsteady lift force spectral density  $\mathcal{L}_i(f_i)$ , on the strip. This, in turn, is a function of an upwash spectrum  $u_i(k_i)$ , a lift-response function  $L_i(f_i)$ , the frequency and quantities associated with the fluid properties, the mean flow, and the strip geometry. Skipping the intermediate steps, the radiated acoustic power associated with the TI noise from each strip can be expressed as shown in equations (9) and (10):

$$\Pi_i^n(f) = \frac{f}{6\rho_0 c_0^3} \mathcal{L}_i(f). \quad (9)$$

The unsteady lift force spectral density is given by

$$\mathcal{L}_i(f) = 16\pi^3 \rho_0^2 \frac{b_i^2 d_i}{\cos \beta^{LE}_i} \left| L_i(\hat{f}_i) \right|^2 U_i u_i(\hat{k}_i), \quad (10)$$

where  $b_i$ ,  $d_i$ , and  $\beta^{LE}_i$  are the semichord, semiwidth, and leading-edge skew of the strip, respectively (indicated in figure 6).  $U_i$  is the Reynolds-averaged sectional inflow velocity to the strip in the strip-fixed coordinate system. The quantity  $\hat{f}_i = fb/U_i$  is known as the sectional reduced frequency. The sectional skew-corrected gust wave number is given by

$$\hat{k}_i = \frac{2\pi f}{U_i \beta^{LE}_i}.$$

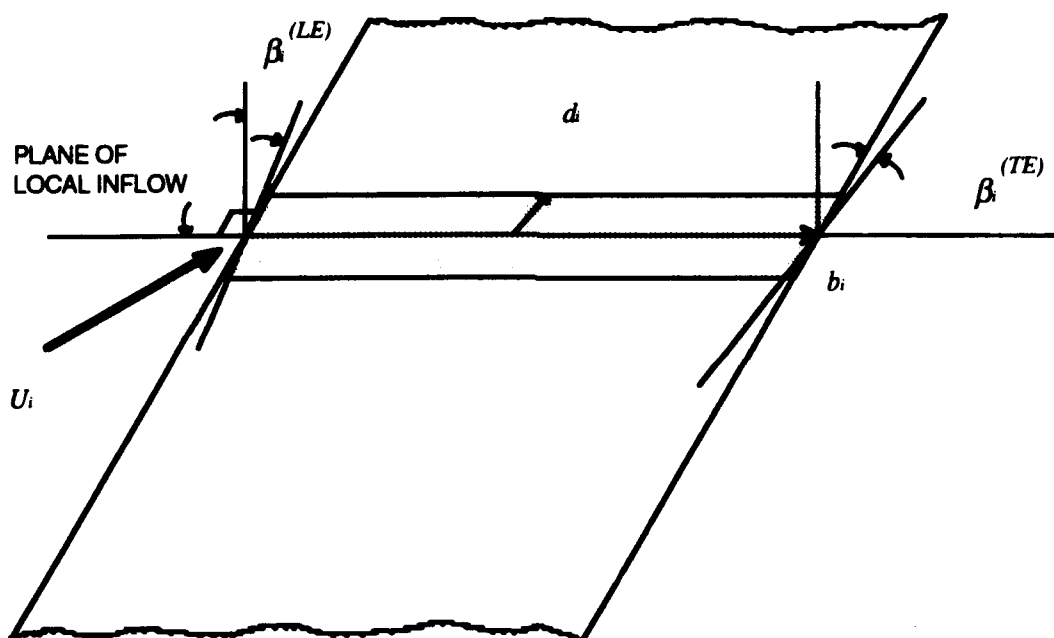


Figure 6. Strip Geometry

Amiet (1975) presents the justification for eliminating all components of the turbulence except the upwash spectrum in computing the radiated sound pressure directly above a strip, as has been assumed by Breit and Dickinson (1990) in the derivation of equation (9). In the absence of a first-principles approach for determination of this quantity, it is necessary to model the physical process empirically.

The upwash spectrum is related to the ingested turbulence intensity spectrum and, in principle, could be either directly measured or derived from the more common measurement of the longitudinal turbulence spectrum (according to a procedure such as that proposed by Breit and Dickinson (1990)). In practice, however, it is convenient to assume that the ingested turbulence is homogeneous and isotropic in the neighborhood of each strip, and to derive the upwash spectrum from one of the various empirical models for such turbulent flowfields.

In particular, Breit and Dickinson (1990) have validated results using the Liepmann model to derive an expression for the upwash spectrum that can be rewritten as equation 11:

$$U_i(\hat{k}_i) = \frac{3u_i'^2 \hat{k}_i^2 \Lambda_i^4}{4\pi[1 + \Lambda_i^2 \hat{k}_i^2]^{5/2}}, \quad (11)$$

where  $u_i'$  and  $\Lambda_i$  are, respectively, the turbulence intensity and integral length scale of the homogeneous isotropic turbulent flow at strip  $i$ .

The details of measurement of the turbulence intensity and the integral length scale, along with the underlying statistical theory are presented in Breit and Dickinson (1990), Hinze (1975), and many other texts on turbulence. In brief, it should be noted that, in practice, the integral length scale is often approximated from the more commonly available integral time scale  $T_i$  by the application of Taylor's frozen-field hypothesis. Hinze (1975) provides the appropriate relation shown in equation (12):

$$\Lambda = u\tau, \quad (12)$$

where  $u$  represents the mean convection speed of the turbulent flow. This approach was employed by Petrie (1991) in the Applied Research Laboratory (ARL) analysis of the turbulent inflow to the COTOP and swirl inducing stator upstream of propulsor (SISUP) propulsors.

The final quantity required for computation of the farfield radiated sound power associated with a single strip of a lifting surface using equation (9) is the lift-response function, which relates the amplitude of the unsteady lift force on the strip to a unit sinusoidal upwash gust. Breit and Dickinson (1990) have tested four such functions—those of Sears, Atassi, Filotas, and Amiet—and conclude (based on validation of the TI noise model by comparison with data, Brown and Gray (1974), from experiments with a Mk 45 torpedo propulsor) that the lift-response function of Amiet is the most appropriate for marine applications.

The Amiet lift-response function accounts for the noncompactness of the lifting surface. It does not account for flight angle, camber, thickness, or skew. Skew, however, has been accounted for in equation (9) using geometrical reasoning. The Amiet lift-response function was originally derived for compressible flows. Application to low-Mach-number flows is justified based on a result of Graham (1970), which relates the skewed-gust and compressible-gust problems via similarity arguments.

The Amiet lift-response function is actually two separate functions that apply to the low- and high-frequency domains separately. Its expression in terms of the reduced frequency  $\hat{f}_i$  and the sectional Mach number  $M_i = U_i/c_o$  is simplified via definition of the following quantities:

$$m_1 = \sqrt{1 - M^2}$$

$$m_2 = \sqrt{\frac{2}{1 + M}}$$

$$\hat{f}_0 = \frac{m_1^2}{8M}$$

$$\hat{f}_1 = \frac{\hat{f}}{m_1^2}$$

$$\hat{f}_2 = \frac{\pi M \hat{f}}{8 \hat{f}_0}$$

$$\hat{f}_3 = \frac{4}{m_1^2} \sqrt{\hat{f} M},$$

where  $\hat{f}_0$  is the cutoff frequency separating the low- and high-frequency domains. These quantities are applicable to each strip via the sectional reduced frequency and the sectional Mach number; the subscript  $i$  associated with the strip under consideration will henceforth be neglected to simplify the presentation.

With these definitions, the Amiet lift-response function is given by equation (13):

$$L(\hat{f}) = \begin{cases} L_<(\hat{f}) \forall \hat{f} < \hat{f}_0 \\ L_>(\hat{f}) \forall \hat{f} > \hat{f}_0 \end{cases}, \quad (13)$$

with the low- and high-frequency functions given by

$$L_<(\hat{f}) = \frac{L_0(\hat{f}_1)}{m_1} \left[ J_0(\hat{f}_2) - i J_1(\hat{f}_2) \right] e^{i 2 \pi \hat{f}},$$

$$L_>(\hat{f}) = L_1(\hat{f}) + L_2(\hat{f}),$$

where

$$L_0(\hat{f}) = \text{Sears lift-response function}$$

$$= \frac{i 2 \pi \hat{f}}{H_1^{(2)}(\hat{f}) + i H_0^{(2)}(\hat{f})}.$$

$J_0(z)$  and  $J_1(z)$  are Bessel functions of the first kind of order zero and one, respectively, while  $H_0(z)$  and  $H_1(z)$  denote Bessel functions of the third kind (otherwise known as Hankel functions) of order zero and one. Each of these functions is, in general, a complex function of a

complex argument. The underlying mathematics are well presented in Lebedev (1972) and Abramowitz and Stegun (1972).

The two components comprising the high-frequency, Amiet lift-response function are given by

$$L_1(\hat{f}) = \sqrt{\frac{2}{\hat{f}}} \frac{Z m_2}{\pi^2},$$

$$L_2(\hat{f}) = \frac{2Z^2}{\pi^2 M \hat{\omega} \sqrt{\hat{f} m_2}} \left\{ \left[ E^*(\hat{f}_3) - Z \right] - \left[ m_2 E^*(\hat{f}_3 / m_2) - Z \right] e^{-im_2^2 M \hat{\omega}} \right\},$$

where

$$Z = \sqrt{-\frac{i}{2}},$$

$$\hat{\omega} = 2\pi\hat{f}.$$

Breit and Dickinson (1990) define the function  $E^*(z)$  as

$$E^*(z) = C(z) - iS(z),$$

where  $C(z)$  and  $S(z)$  are Fresnel integrals. However, for real values of the argument, using identities, (Lebedev (1972), pp. 16-23), this function can be rewritten more concisely as

$$E^*(x) = Z\Phi(Z\sqrt{-\pi x}),$$

where  $\Phi(z)$  is the probability integral

$$\Phi(z) = \frac{2}{\pi} \int_0^z e^{-z'^2} dz'.$$

Substitution of this form into a later version of program BBN2 might save some computation.

## 2.2 TE NOISE MODELING: REFORMULATION IN PROGRESS

Program BBN2 incorporates two models for predicting lifting surface TE noise: the continuous-spectrum noise model of Howe (1978), Howe (1988), and the empirical method for continuous-spectrum and vortex-shedding noise of Hayden (1972). Under the CCAPS SIA effort, the first method was used extensively, while the second was not even tested, since the propulsors under consideration have been specifically designed to prevent singing and other narrowband TE vortex-shedding effects.

A reformulation of these models is in progress. The reader is referred to Breit and Dickinson (1990) for details of both of these models as currently formulated. Application of the existing TE model incorporated in program BBN2 is documented in section 4.2.

## **2 PROPULSOR GEOMETRY AND OPERATING CONDITIONS**

Input to program BBN2 includes the standard International Towing Tank Conference (ITTC) propulsor geometry (based on a cylindrical coordinate system) and analogous fin geometry (for foils). Also required are data specifying the inflow (including the propeller shaft speed, vehicle speed, and information about the ingested turbulence), the boundary layer convection velocity, and a one- or two-sided TE pressure spectrum, usually chosen from a library of spectra associated with typical TE geometries.

### 3. VALIDITY OF THE MODEL

In accordance with the SIA objectives outlined in section 1, the semianalytic, physics-scaling, propulsor noise model was tested to varying levels of detail on each of the CCAPS SIA candidate propulsors. This section is devoted to a detailed review of the predictions of the model for two of the candidates: the SISUP propulsor and the COTOP. Results for the remainder of the candidates are presented in section 4.

#### 3.1 COMPREHENSIVE COMPARISON: THE SISUP PROPULSOR

The SISUP design was conceived as a compromise between the efficient and geometrically simple counter-rotating propellers (CRPs) and the mechanically simple shrouded propulsors currently employed on the fleet torpedoes. Instead of a rotating upstream blade row, the SISUP is fitted with a stator blade row consisting of eight inlet guide vanes. This stator induces swirl in the inflow to the rotor, which is located downstream of the stator and is fitted with six skewed blades. The design of the two blade rows is intended to result in a swirl-free slipstream, resulting in efficient torque-free operation.

The efficiency of the SISUP at medium speed under design operating conditions  $\eta_D = 0.92$  is about midway between that of the CRPs and the less efficient shrouded propulsors. The nominal rotor diameter is  $D = 0.460$  m. At medium speed, SISUP is designed to deliver 175 hp.

SISUP was tested in the Atlantic Applied Research Corporation (AARC) AWT at a top speed of 36.6 m/s. It was found that, as expected, SISUP is a relatively quiet propulsor in straight and level flight. Early predictions of the broadband direct-radiated noise of the SISUP propulsor using program BBN2 are presented in figures 7 and 8, where they are compared with AWT results. In examining these results, recall from section 1 that the AWT results essentially reflect only the direct-radiated noise because, since the acoustic impedance between the propulsor material and air is so mismatched, there is very little excitation of the structure.

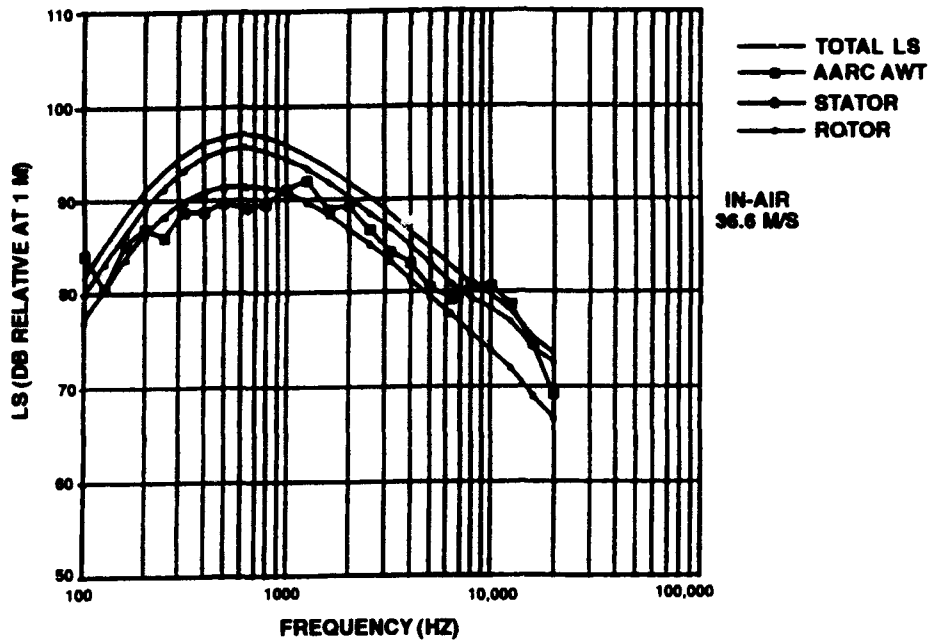


Figure 7. SISUP: Results of Semianalytical Noise Model Compared With Acoustic Wind Tunnel Measurements

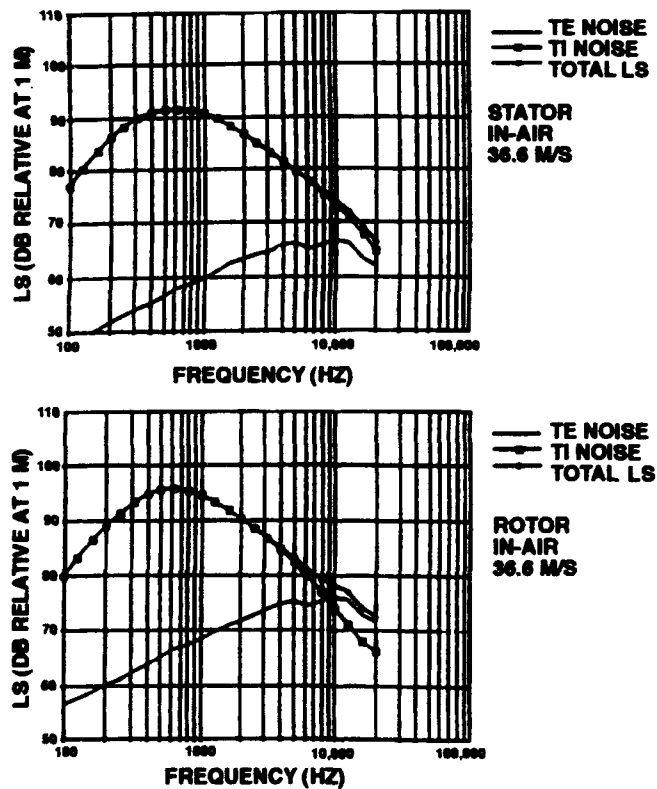


Figure 8. Components of Direct Broadband SISUP Radiated Noise



Several noteworthy conclusions can be drawn from figures 7 and 8:

1. The prediction is within 5 dB of the measurement across most of the frequency domain presented, except in the region between 300 Hz and 1000 Hz, where the deviation is never more than 8 dB;
2. The prediction captures the TE noise hump (albeit very slightly), which peaks at about 10,000 Hz;
3. The prediction provides some estimate of the magnitude of each source of the excitation (stator and rotor TI and TE noise), while such information cannot be deduced from the AWT measurements alone.

It can be seen from these figures that the primary direct broadband radiated noise source of the SISUP propulsor is that associated with turbulence ingested by the rotor. Similarly, the TE noise is also dominated by the rotor.

The most likely source of differences between the predicted and experimental data is the TI data used to characterize the inflow to the propulsor. Firstly, the TI data used was sample data provided by BBN measured on the quiet torpedo (QT) with QT propulsors by Brown and Gray (1974). Secondly, no account has been made of the effect of the upstream stator on the inflow field. Finally, differences between the data sets in the neighborhood of the TE noise peak can be attributed to a lack of detailed knowledge about the boundary layers of the stator and rotor blades and the associated pressure spectra.

Plans for future development of the model include additional validation using the actual SISUP inflow data measured as part of the CCAPS SIA effort. In conjunction with the ongoing development of various NUWC Division Newport propulsor design and analysis tools, a capability will soon be in place to more accurately predict the effect on the inflow of successive blade rows. This capability will be incorporated with a future version of the propulsor physics-scaling noise model. Finally, if cases were to arise for which TE noise was important to the overall propulsor noise spectrum, the TE noise peak could be predicted more accurately by performing more detailed analyses of the stator and rotor blade boundary layers.

### **3.2 EFFECT OF TI DATA: THE COTOP**

One of the shrouded CCAPS candidate propulsors, known as COTOP, is fitted with stators both upstream and downstream of the rotor. The most recent COTOP prototypes are provided with other quieting features, many of which are classified.

The COTOP was modeled to a level of detail including the rotor only, with the effect of the other components (the two stators and the shroud) estimated. In particular, it was assumed that blade rows of the COTOP radiate equally, and that the noise from the blade rows dominate that from the shroud. Thus, the spectra have been computed by adding 4.77 dB to the prediction for the rotor alone, representing three equal sources. A more detailed prediction using program BBN2 is planned, for which each blade row and shroud will be modeled.

For the early SISUP predictions presented in section 3.1, TI hydrodynamic data from Brown and Gray (1974) were used. During the CCAPS SIA effort, new TI hydrodynamic data were measured at the Penn State University (PSU) Applied Research Laboratory (ARL) in the Garfield Thomas Water Tunnel (GTWT) for both the SISUP propulsor and the COTOP. Thus, two computations were performed for the COTOP: one for the original QT data provided with program BBN2, and one using the actual TI data measured during the CCAPS SIA effort. The

TI data used in the two computations are presented in figure 9. The two data sets shown are the axial component of turbulence intensity and the integral length scale, both plotted versus radius nondimensionalized with respect to the rotor radius.

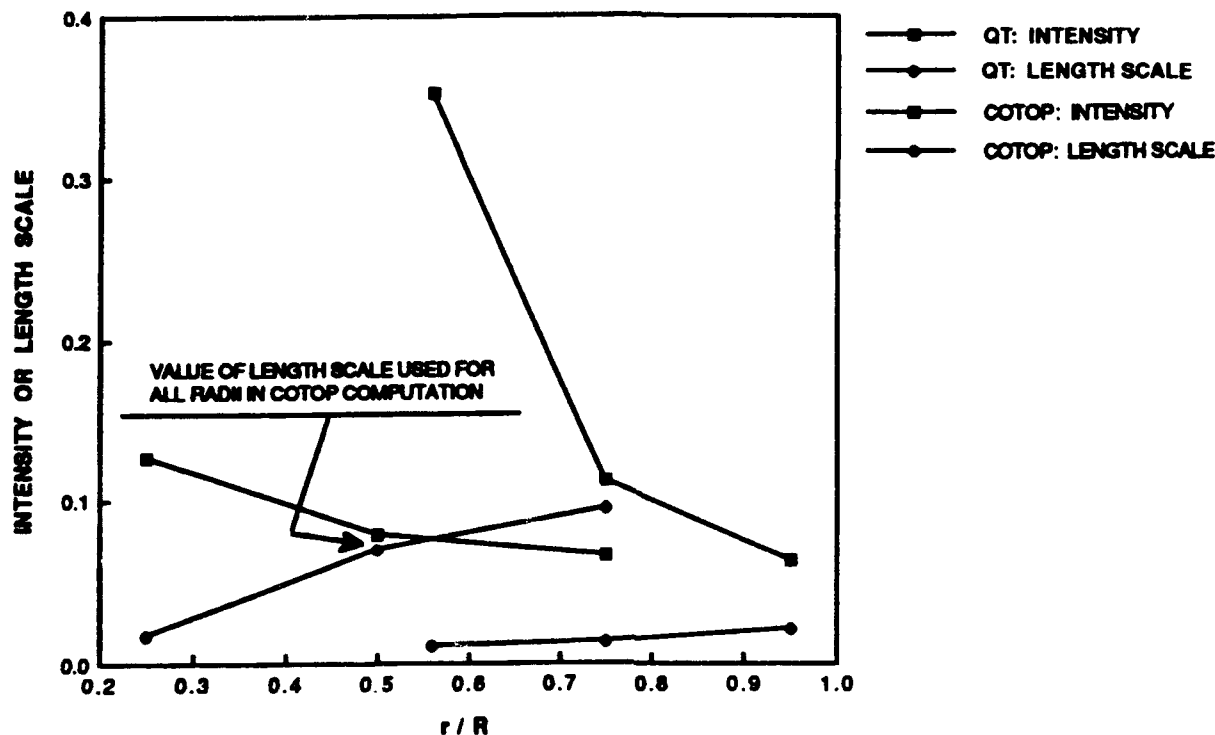


Figure 9. TI Data Used for SISUP and COTOP Analysis

The effect of using CCAPS SIA data versus the older data set can be seen in figure 10. Notice that the source level predicted using the COTOP TI data is lower across most of the frequency domain of interest than that predicted using the QT TI data. This is mostly due to the reduced turbulence intensity reported for the COTOP. The most outstanding difference between the two predicted spectra is the change in frequency of the TI peak. When the COTOP TI data are used, this peak occurs at approximately 200 Hz, versus approximately 700 Hz when the QT TI data are used. This effect is due to the increased integral length scale of the COTOP TI data.

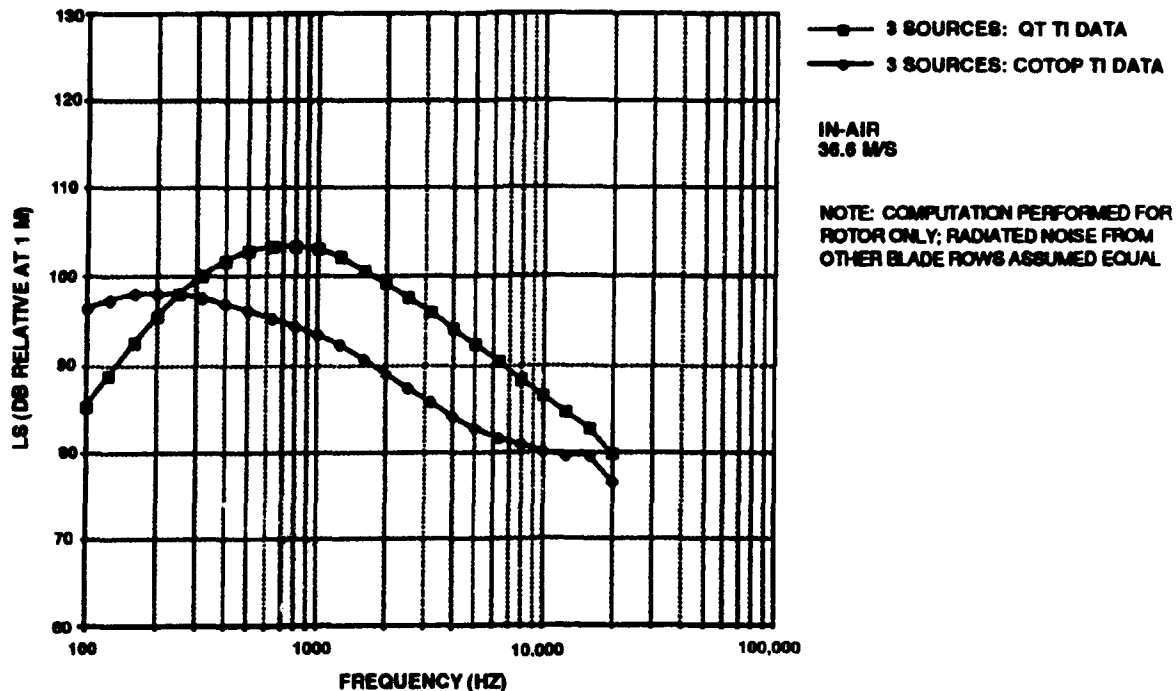


Figure 10. Effect of Using Accurate TI Data in COTOP Computation

The importance of turbulence in the inflow field is thus apparent. A better idea of the potential payoff from reducing turbulence ingested by the propulsor could be provided by arbitrarily varying the turbulence intensity and length scales over a physically meaningful range. Such a parametric study is planned as part of a future application of the propulsor physics-scaling noise model.

Note that the TI data were measured over two different ranges of spanwise locations for the QT and the COTOP data, and that some type of extrapolation is required to provide data for each blade strip if the QT data are used. As discussed in section 5, the specification and use of all TI and boundary-layer data in program BBN2 should be checked to ensure that consistent and rational approximations have been employed.

It should also be noted that the choice of the integral length scale associated with the ingested turbulence was critical to these computations. As depicted in figure 9, the length scale used in the computation was taken as constant over the entire span, with a value equal to that predicted by Taylor's hypothesis at  $r/R = 0.5$ . This was found to yield better results than applying Taylor's hypothesis to the measured data at each point. It is suspected that Taylor's hypothesis breaks down near the root and tip due to inhomogeneity and anisotropy of the turbulence field near the hub and shroud.

### 3.3 COMPARISON WITH OTHER MODELS

Recently, other institutions have been implementing similar models, most notably AARC and ARL. Preliminary information indicates that the theories for these other models are based essentially on those outlined in section 2.

During the CCAPS SIA effort, it was discovered that the coordinate system used by AARC, which is based on cones accounting for the shape of the hub, seems to more accurately capture certain details of the noise spectra for some propulsors. This process is discussed in more detail in section 4.

#### 4. ADDITIONAL EXAMPLES

Aside from the SISUP and COTOP propulsors, five other propulsors were either candidates for the CCAPS program under the SIA effort or important to the project for historical or technology assessment reasons.

The baseline propulsor was that associated with the Mk 48 and Mk 48 ADCAP heavyweight torpedoes, the Alpha III propulsor. This propulsor is also designated A3(RR), for Alpha III radial or regular rotor. Under the modeling effort described herein, the geometry of this propulsor was acquired in the form of inspection coordinates and entered manually. Additional manipulation will be required prior to noise modeling of the A3(RR) using program BBN2. The A3(RR) has been a successful design as it is fairly quiet and performs reasonably well from the standpoint of powering, directional stability, and maneuverability.

Unfortunately, the A3(RR) does not meet the CCAPS noise goal, even at low speed. Since its design in 1957, various remedies have been considered, the most important of which has been the re-examination of the Alpha III skewed rotor or A3(SR). This rotor was on the drawing board as early as 1958, but only recently has it been given serious consideration as a replacement for the A3(RR). The principal modification incorporated in the A3(SR) design is the addition of skew to the rotor. As outlined in section 2, theory indicates that, aside from the well documented benefits for reducing blade-rate tonals, skew can have an important effect in reducing direct broadband propulsor-radiated noise.

The reader should be aware that several related designs exist falling under the name Alpha III skewed rotor, usually designated according to their powering performance in terms of the speed at which they can drive the Mk 48 ADCAP heavyweight torpedo at design rotation rate. Thus, the A3(SR) M-3 propulsor falls short of medium speed by 3 knots, while the A3(SR) M-7 falls short by 7 knots. The A3(SR) propulsor was partially modeled using program BBN2 as part of the CCAPS SIA effort; results are presented in this section.

The A3(SR) M-7 skewed rotor is also designated EXR1. This version of the rotor is currently being considered for redesign to drive the Mk 48 ADCAP heavyweight torpedo at medium speed at design rotation rate.

The NUWC torpedo propulsor (NUTOP) incorporates the A3(SR) in combination with other quieting features, the most notable of which is the application of shroud-mounted appendages. The numerical broadband direct-radiated propulsor noise modeling effort described below has not yet been developed to the level of detail at which such differences can be detected. Thus, the results presented below can be thought of as rough predictions applicable to most versions of the A3(SR), including NUTOP.

Two other propulsors were not actually candidates under the CCAPS SIA effort, but are considered very important technologically. These propulsors are the high and low RPM counter-rotating propellers (CRPs), designated herein as CRP(HI) and CRP(LO), respectively. The great advantage of CRPs is their high efficiency, which results from the thrust distribution between the two blade rows, the absence of a drag-producing shroud, and the necessity of providing a swirl-free wake. However, these propulsors are mechanically complicated, since they are driven by concentric counter-rotating shafts.

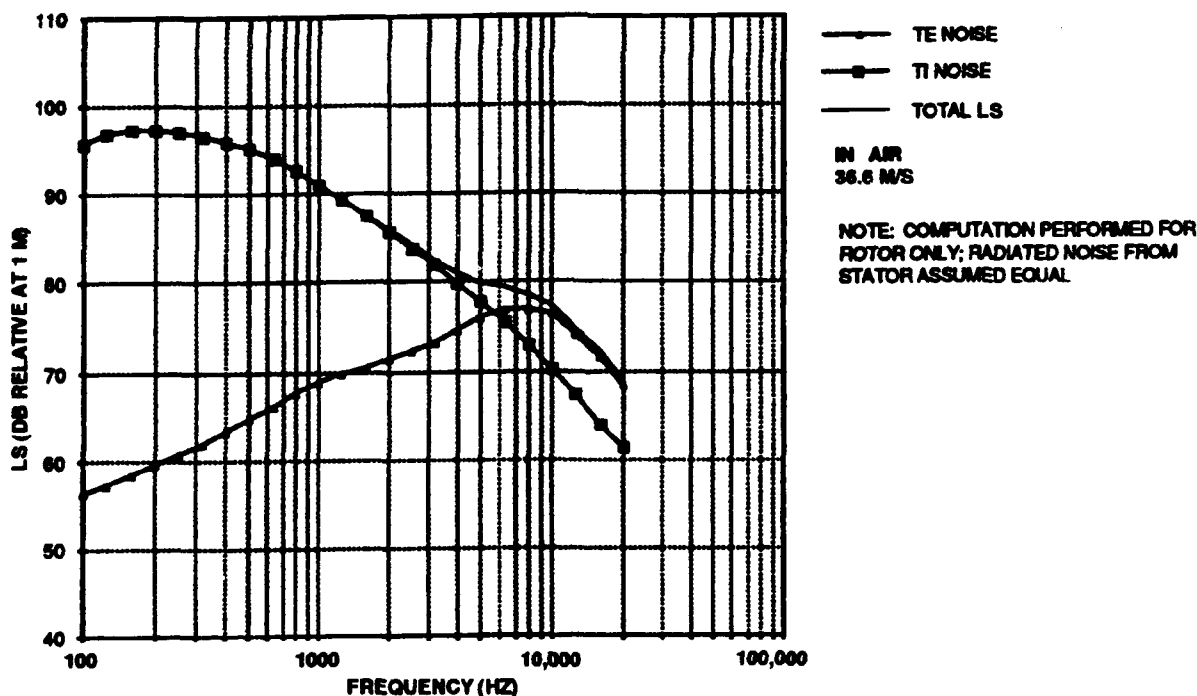
#### 4.1 PREDICTIONS FOR THE CANDIDATE PROPULSORS

Selected operating conditions in the AWT at 36.6 m/s and other details about the various propulsors discussed above are presented in table 1. Also shown are the equivalent parameters for the SISUP and COTOP propulsors discussed in section 3, which are provided for comparison purposes.

*Table 1. Selected Data for CCAPS Candidate and Related Propulsors*

		SISUP	CRP (HI)	CRP (LO)	A3 (RR)	A3 (SR)	NUTOP	COTOP
Blade Number		8x6	6x4	6x4	13x12	13x12	13x12	
Efficiency		0.920	0.960	0.950	0.840		0.830	0.800
Rotor Diameter	m	0.460	0.427	0.419	0.340	0.340	0.340	0.315

Of the seven, only the open propulsors were modeled to a level of detail including the two blade rows. The model for the A3(RR) rotor is in progress. None of the models have included the fins or any shroud, although the fins of the buoyant test vehicle (BTV) were modeled, as is discussed below. Future application of the propulsor physics-scaling noise model will include complete models of the A3(RR) and all variants of the A3(SR). Eventually, the noise radiated by the appropriate stabilizing and control surfaces will also be predicted. The results of predictions for the A3(SR) and the high and low RPM CRPs are presented in figures 11 through 15.



*Figure 11. A3(SR): Results of Semianalytical Noise Model*

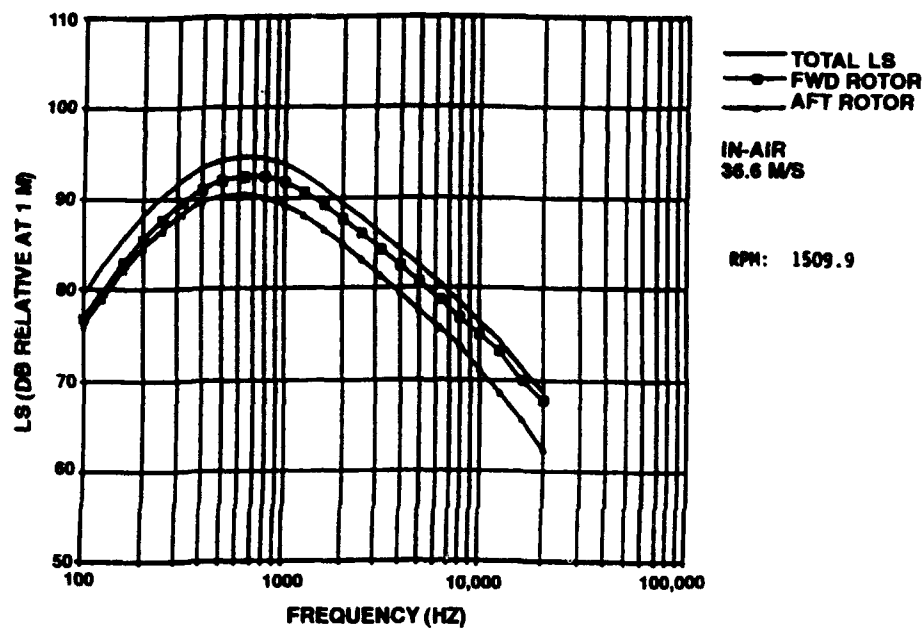


Figure 12. Low RPM CRP: Results of Semianalytical Noise Model

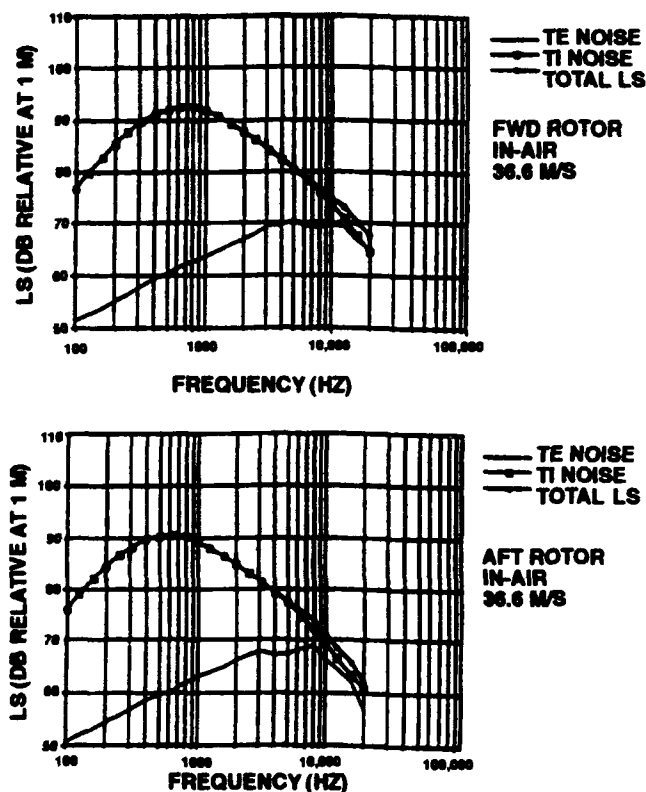


Figure 13. Components of Direct Broadband Low RPM CRP Radiated Noise

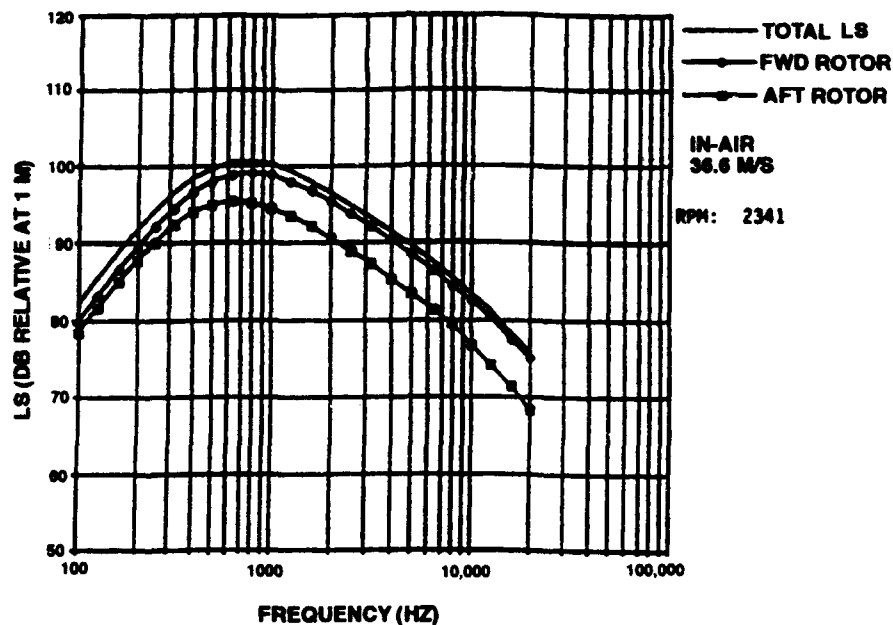


Figure 14. High RPM CRP: Results of Semianalytical Noise Model

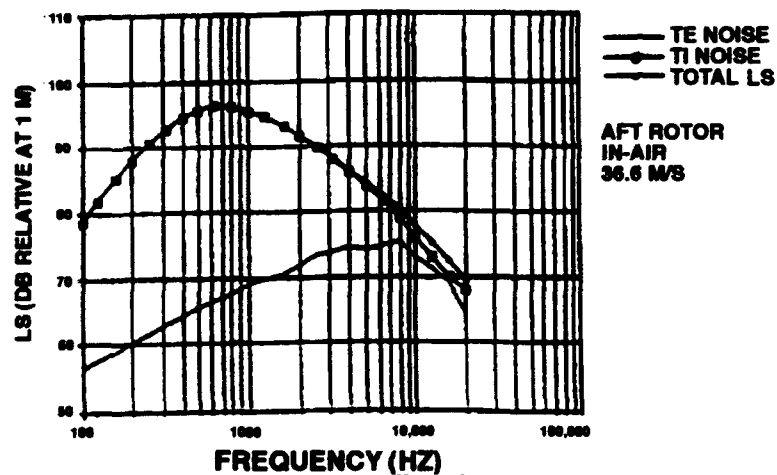
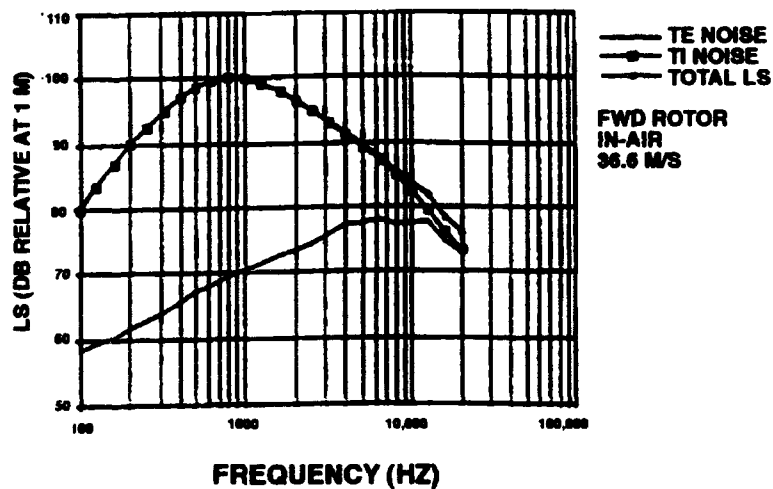


Figure 15. Components of Direct Broadband High RPM CRP Radiated Noise

In figure 11, the TI and TE noise components are presented for the rotor computation, augmented by 3.01 dB across the spectrum. As was done for the COTOP, the A3(SR) (including NUTOP) was modeled to a level of detail including the rotor only (that is, results of program BBN2 were incremented by 3.01 dB across the spectrum to account for the downstream stator). The COTOP TI input data (measured as part of the CCAPS SIA effort and discussed in section 3.2) was used in the A3(SR) computation.

Figures 12 and 13 show the results for the low RPM CRP predictions in the same format as that used in section 3.1 for presentation of the SISUP predictions. Figures 14 and 15 present the results for the high RPM CRPs in the same format. The Mk 45 TI input data of Brown and Gray (1974) were used in both the low and high RPM CRP computations.

A summary graph showing the predicted total source levels for each of the SISUP, COTOP, A3(SR), and low and high RPM CRPs is presented as figure 16. According to these predictions, the TI noise peak of the open propulsors occurs between 600 and 700 Hz, while that for the ducted propulsors occurs at approximately 200 Hz. These noise peak variations are caused by two different TI input data sets used in each of the computations. The TE noise peak is discernible in the predicted spectrum of each open propulsor. It is more pronounced in the predicted spectra of the ducted propulsors, not because TE noise is more dominant, but because the TI noise for the ducted propulsors is more dominant at lower frequencies due to the larger integral length scale associated with the TI input data used in those predictions.

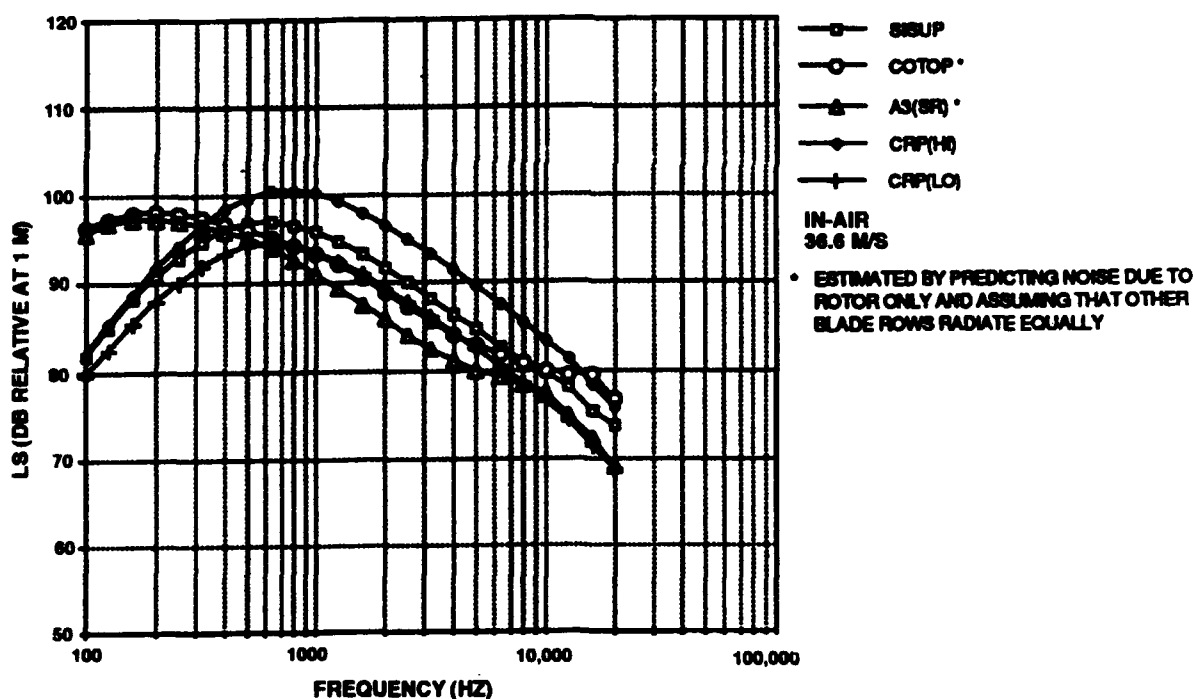


Figure 16. Predictions of the Direct Broadband Radiated Noise for the CCAPS Candidate Propulsors

It should also be noted that the high and low RPM CRP predictions bracket that of the SISUP (above and below, respectively). Similarly, the predicted A3(SR) direct noise spectrum is quieter than the predicted COTOP spectrum.

Although not presented in this document, AARC provided predictions for several of the CCAPS SIA candidate propulsors developed using their physics-scaling propulsor noise model.



As was discussed in section 3, their model is based on the same theory as is program BBN2 and, in fact, the results for most of the propulsors were very close. For the low RPM CRPs, however, the AARC prediction was quieter than the results of program BBN2 presented above. In fact, the AARC prediction was closer to the AWT results over most of the frequency range. It is suspected that the AARC input geometry scheme is more accurate, being based on conical (rather than cylindrical) sections, and that the loss of accuracy near the blade root is degrading the program BBN2 prediction.

## **4.2 PREDICTIONS AND COMPARISONS FOR BTV FINS**

To investigate the effects of design changes on flow noise, i.e., direct noise due to the turbulent boundary layer and the reradiated noise associated with its excitation of the hull structure, NUWC Division Newport uses a BTV. This vehicle is released from the floor of the test range. Since it is positively buoyant, it does not require a propulsor, prime mover, energy source, or control fins, thus eliminating those noise sources. Speed is controlled by the amount of ballast. Since no propulsor or control fins exist, the vehicle is directionally unstable and requires rather large stabilizing fins at the stern.

At slow speeds, it is suspected that fin noise dominates flow noise. In particular, since the fins project well beyond the edge of the boundary layer and are thus not subject to a turbulent flow field over most of their leading edge, fin TE noise should be the dominant vehicle noise source at slow speeds.

During the CCAPS SIA effort, an intensive BTV testing program was initiated. One of the objectives was to assess the effect of fin noise on the total vehicle signature.

A parallel effort was initiated by the author to model the BTV fins using program BBN2. The purpose of this effort was not to predict the direct noise exactly, but to predict trends in the fin signature associated with changes in the design.

First, a slender-wing design method was developed to choose various fin planforms intended to provide the same stabilizing moment as the original rectangular fins. Each planform, including the original, was then modeled using program BBN2. The results are presented in figures 17 and 18.

Figure 17 shows results for the straight-edged planforms, including the original rectangular fins, a delta wing, and a delta wing with a swept trailing edge. Figure 18 shows results for fins with so-called gothic planforms which, under slender-wing theory, are known to have higher lift-drag ratios than either the rectangular or delta wings. The first figure shows three planforms and the associated TE noise spectra. The second figure is similar, except that various hydrodynamic and geometric data are also shown.

It should be noted that the TI noise component was modeled as part of this effort, but that its contribution to the total fin signature is so small that the results are off the scales of each graph in figures 17 and 18. This is additional evidence that, as expected, direct TE noise completely dominates direct TI noise over the entire spectrum of the BTV fin signatures.

For all the wings (except the original), it was intended to increase skew, which is known to decrease the TE noise signature. For the gothic wings, it was hoped that the improved hydrodynamic efficiency would be accompanied by a lower direct-noise signature.

As can be seen from the figures, however, the wing with the lowest direct-noise signature is the delta wing with the skewed trailing edge, while that with the highest is the original

rectangular wing. A reduction of about 7 dB at the spectrum peak is achieved with the skewed delta wing.

These results should be used with extreme care, since the structural transfer gain of each of the wings has not been considered. In fact, it is expected that the fin with the lowest direct-noise signature will have the greatest transfer gain. Thus, since reradiated noise can be extremely important to the total signature in water, the skewed delta wing might, in fact, have the worst signature.

Such a situation represents a classic problem in optimization. If an acoustic figure of merit were developed which characterized the fins, and the structural-response problem could be solved to the same accuracy as the direct-noise problem has been, the optimal skew distribution could be predicted using standard methods.

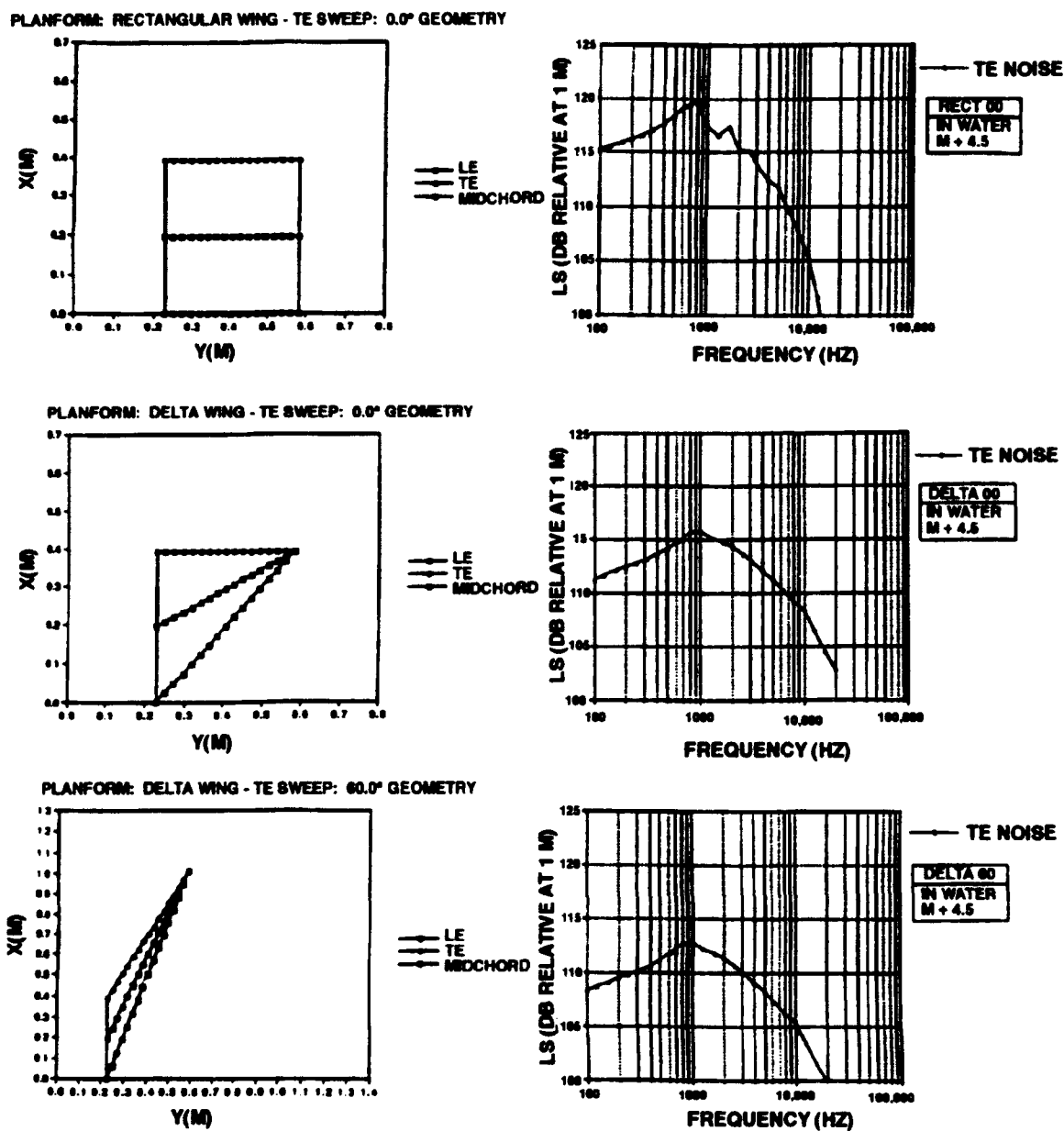


Figure 17. Straight-Edged BTV Fins and Their Predicted Direct Broadband Noise Signatures

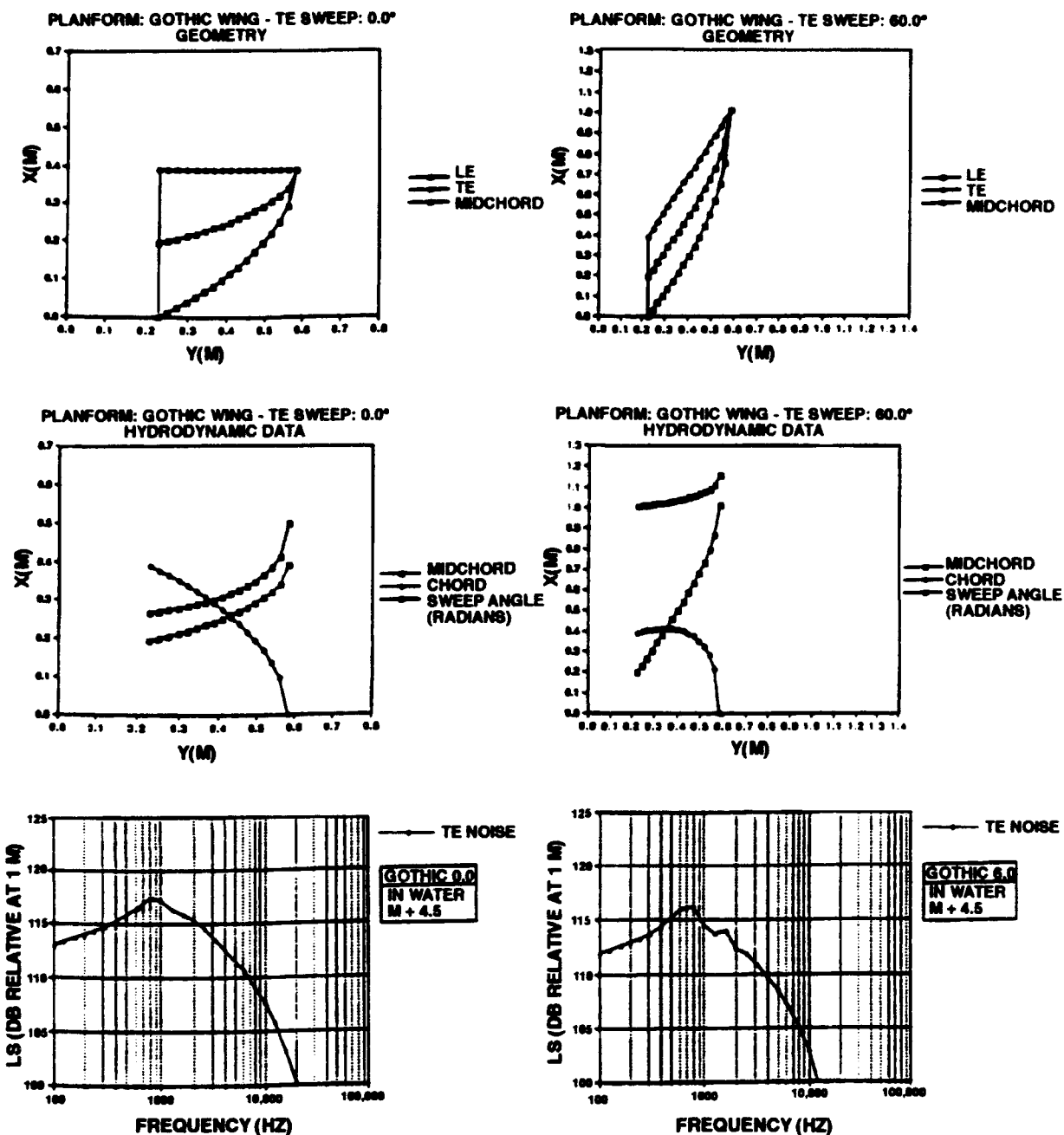


Figure 18. Low Aspect-Ratio BTV Fins and Their Predicted Direct Broadband Noise Signatures

## **5. CONCLUSIONS AND RECOMMENDATIONS**

This report documents the implementation of a NUWC Division Newport physics-scaling, broadband, radiated noise model for use in the design and analysis of weapon propulsors. Among the accomplishments were the following:

1. Identification, procurement, installation, and validation of program BBN2 which represents an implementation of the physics-scaling, broadband, radiated noise model;
2. Upgrading of the program to standardize the input and allow analysis of propulsors consisting of multiple blade rows and ducts or bands; and,
3. Application of the model to various CCAPS SIA candidate propulsors, including the SISUP, the COTOP, the high and low RPM counter-rotating propellers, and the Alpha III skewed rotor.

In the process of performing this effort, the underlying theory was reviewed and partially reformulated in the more direct presentation and simplified notation outlined in section 2. In pursuit of the long-term goal of development of a complete first-principles propulsor-radiated noise model for use in the design and analysis of submarine warfare systems, the more general theory of noise radiated from moving bodies was reviewed and partially reformulated for consistency with the current model.

Also as part of the effort, the model was shown to have reasonably good agreement with other Division noise-modeling procedures, notably acoustical wind tunnel predictions of broadband direct-radiated noise.

The effect of ingested turbulence level was examined, and a procedure was tested for reducing data from propulsor-specific, TI measurements to a form useful for input to the model.

By analyzing various BTV fin designs, it was demonstrated that the model can be used to help develop noise-related trends associated with designs.

A substantial background effort was also performed to accomplish the CCAPS SIA noise-modeling objectives outlined in section 1, namely the collection of various propulsor geometry and operational data and its reduction to one standard format.

Recommendations for additional development can be categorized as follows.

### **5.1 NEAR-TERM REFINEMENT OF THE MODEL AND PROGRAM**

An heuristic analysis of the input to program BBN2 uncovers various deficiencies:

1. The cylindrical coordinate system does not allow for the typical tapered hub shapes associated with torpedoes. As is documented in section 4, this can lead to inaccuracies in the results;
2. Specification of the detailed propulsor velocity field could be performed by incorporating a lifting-surface model with the program. This would remove some of the ad hoc specification of data currently required;

3. No prediction of the effect of upstream blade rows on modification of the inflow turbulence is incorporated with the model, requiring that, for accurate analyses, complicated and expensive turbulence measurements must be made between blade rows;

4. Specification of the length scales associated with the ingested and blade boundary-layer turbulence spectra requires propulsor-specific empirical knowledge;

5. Other information associated with the blade boundary layers also requires propulsor-specific empirical knowledge.

Upgrades to other NUWC Division Newport computational propulsor design and analysis tools should be applied directly to the next generation of program BBN2 to remove some of these deficiencies.

In particular, the noise model should be integrated with the Axisymmetric Propulsor-Hull Interaction Program System (APHIPS) and the Axisymmetric Propulsor-Hull Interaction Design System (APHIDS). This would not only remove some of the ad hoc input currently required for use with program BBN2, but would add significant value to the propulsor design and analysis programs in the form of a broadband noise assessment capability. Planned upgrades to the APHIPS-APHIDS program suite would eliminate deficiencies 1 through 3 listed above.

Other deficiencies could also be eliminated in the near term. For example, separation of the propulsor direct-radiated noise problem into broad and narrowband subproblems is intellectually convenient, but eliminates the usefulness of results of each model standing alone. The next logical step in the development of a Division computational propulsor noise model is the combination of the model represented by program BBN2 with a physics-scaling narrowband noise model, such as the one provided to Newport operations by ARL as part of their CCAPS SIA deliverables. The ARL model requires installation, validation, and a considerable investment of understanding before an effort to combine the two programs can begin.

Similarly, separation of the complete propulsor-radiated noise problem into direct and structural reradiation subproblems eliminates the usefulness of the results of each model standing alone. An effort should be supported that would allow straightforward incorporation of the results from reverberant tank experiments. A technique such as that proposed by Uhlman, Kirschner, and Abbot, would be extremely useful in the design and analysis of weapon propulsors.

Finally, the input and output to the program could be drastically streamlined without an overwhelming investment. A tremendous savings could be realized by providing the program graphical output conforming to the Division's standards. Much of the CCAPS SIA effort was spent transferring data between computer systems, performing nondevelopmental manipulation of the data, and then producing graphical output that was considered acceptable for presentation. Graphics tools being developed by the Technical Support Staff under other funding are nearly complete and could be applied immediately to program BBN2 or its descendants to eliminate unnecessary transfer and manipulation of data and the associated out-of-house costs.

## **5.2 APPLICATION OF THE MODEL**

Even in its current rudimentary form, program BBN2 can provide useful information, as has been documented in sections 3 and 4. The effort started under the CCAPS SIA program should continue, namely applying program BBN2 to the Alpha III radial rotor, and upgrading each of the propulsor models to incorporate all components, including the fins.

When new propulsor or fin designs come under consideration, it should become the Division's standard practice to analyze them using the physics-scaling noise model.

Finally, the noise model should be run prior to any extensive experimentation effort associated with direct broadband propulsor-radiated noise to estimate the expected results and perhaps refine the test plan.

### **5.3 LONG-TERM MODEL DEVELOPMENT**

In the long term, the empiricism associated with the noise model should be continually eliminated. The accomplishment of a NUWC Division Newport corporate objective to become a leader in the development of first-principles design and analysis tools for propulsor hydrodynamics and noise analysis would realize tremendous savings over the current costly design cycle.

The Division's development of Navier-Stokes solvers should continue, and be partially directed toward providing input to program BBN2 in the form of ingested turbulence-intensity spectra and integral-length scale data. Such computational tools could also provide data associated with the blades themselves, namely the blade boundary-layer characteristics and the TE pressure spectra.

Finally, finite or boundary element methods should be applied to the propulsor structural reradiation problem.

### **5.4 DEVELOPMENT OF A NUWC DIVISION NEWPORT PROPULSOR-GEOMETRY STANDARD**

Each step in the hydrodynamic and hydroacoustic analysis of weapon propulsors under the CCAPS SIA program has been hampered by lack of a standard geometry-archiving procedure. In the process of obtaining geometric and operational data for the examples presented in sections 3 and 4, it was clear that each contractor assigned to the prototyping of a particular propulsor controls not only the format and parameterization of the geometric data, but also its release to the Division.

Geometry standards for propulsors have been in existence for many years, the most notable being that of the International Towing Tank Conference (ITTC), used (with only minor variations) by Navy laboratories such as the Naval Surface Warfare Center; professional societies such as the Society of Naval Architects and Marine Engineers; academic institutions such as Massachusetts Institute of Technology, The University of Michigan, and Webb Institute of Naval Architecture; and contractors such as BBN Systems and Technologies and Atlantic Applied Research Corporation. This standard, most likely, will be upgraded to reflect recent developments in propulsors in the near future and periodically in the years to come.

It is recommended that the Division adopt such an accepted standard, extended where necessary to reflect features peculiar to submarine weapon propulsors, and that all exchanges of technical information associated with the propulsors adhere to the accepted standard. This would eliminate much needless nondevelopmental manipulation of information.

In adopting such a standard, it should be noted that the hydrodynamic data required for analyses such as those presented herein are far less complicated than the detailed design data typically required for machining, which, for the Newport operations, is archived using computer-aided design systems.

Any Division propulsor-geometry standard should provide detailed information about the shape of the trailing edge along the span of each propulsor component, in addition to the other distributed and local data specified in the ITTC standard, such as skew, rake, chord, thickness, camber, and leading-edge radius.

Additionally, the standard should be comprehensive enough to specify the entire propulsor geometry to the level of accuracy required for proper modeling of each component. In particular, a conical section definition represents the minimum level of sophistication required to obtain accurate results from a program such as BBN2, as evidenced by the degraded prediction of the low RPM CRP spectrum presented in section 4.

## **5.5 COMPATIBILITY OF EXPERIMENTATION AND MODELING**

Finally, the cost of the Division's design cycle could be reduced by accounting for computational models in the test plans. For example, the results of each propulsor experiment should include appropriate input to all available NUWC Division Newport semiempirical computational design and analysis tools.

In the case of program BBN2, the following data can be extracted from tests in wind tunnels, water tunnels, tow basins, or reverberant tanks, provided their need is anticipated in the associated test plan:

1. Basic steady inflow data consisting of velocity vectors measured just upstream of each propulsor component (blade rows, shrouds, bands, and fins) at a sufficient number of points to resolve the boundary layer or wake of each upstream component, including the hull. Also required are the mean wake (which is related to the average of the axial component of the steady inflow velocity vector) and the hull boundary-layer thickness (which can be derived from the profile of the component of velocity tangential to the hull);
2. Turbulence-ingestion data consisting of (at least) the axial component of turbulence intensity and some measure of the integral length scale of the turbulent flow just upstream of each propulsor component;
3. The slipstream contraction ratio, i.e., the ratio of the thicknesses of the hull boundary layer upstream and downstream of the propulsor component under consideration;
4. TE pressure and integral length-scale spectra, if not already available from archived data. Such data need not be measured on the actual propulsor, which would be very costly. Instead, equivalent fixed-wing measurements should be made, similar to those by Blake (1975) or Brooks and Hodgson (1981);
5. Verification of the TE turbulent boundary-layer convection speed.

Under the CCAPS SIA effort, items 1 and 2 were addressed for several of the propulsors (so that item 3 could have been derived), while items 4 and 5 were not. However, if all the data had been presented in a more standard fashion, in a Division-specified format on electronic media, the information would have been immediately useful at a much lower cost.

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